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Radiation Physics and Chemistry 77 (2008) 115–120
Radiation Physics and Chemistry
www.elsevier.com/locate/radphyschem

Simulation study on detection efficiency of plastic scintillating fiber under γ-ray radiation

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Received 13 March 2007; accepted 5 September 2007

Abstract

The detection efficiency of the plastic scintillating fiber (PSF) for γ-ray radiation is presented through Geant4 simulation. The incident γ-rays with energy of 100–10,000 keV are considered. Absorption efficiency and scintillating response of PSF are also obtained, and the simulated results are consistent with the theoretic ones. From simulation, the main important factor of detection efficiency in the energy range is the absorption efficiency of the scintillating material. The cross talks in a fiber array are also discussed. These results could probably provide some ways of using PSF as a γ-ray imaging detector in certain applications.

PACS: 29.40.m

Keywords: Plastic scintillating fiber; Detection efficiency; Cross talk

1. Introduction

With the increasing demand of NDE for dense and large objects, great efforts are made to improve the performance of high energy γ-ray (usually from a few hundred keV to about 10 MeV) imaging system (Li et al., 2003; Izumi et al., 1993; Vorogushin et al., 2003; Davis et al., 2000). To increase the efficiency or the sensitivity for high-energy γ-rays, a thicker scintillation material is usually desired. However, an increased thickness of the scintillator would result in a larger isotropic spreading of light generated in the scintillation materials, reducing the spatial resolution of the imager. Thus, a compromise or a balance between the spatial resolution and γ-ray absorption efficiency is needed in designing and constructing a γ-ray imager. Furthermore, due to the high cost of scintillation materials, it is desirable to find a simpler and more cost-effective approach in constructing detectors for hard γ-ray imaging.

In recent years, the plastic scintillating fiber (PSF) has been applied in many fields, such as particle tracking in high-energy particle physics, calorimeters, etc. The main advantages of PSF are its fast response, flexibility and electromagnetic immunity (White, 1988). In a scintillating fiber γ-ray detector, a portion of the light is converted from the incoming γ-ray within a fiber and channeled along the fiber through total internal reflection; an extra mural absorber (EMA) would absorb the remainder (White, 1988). Such a design might do not deteriorate too much the spatial resolution as the length of the fiber increases. The results of several studies have been reported using this design for low-energy X-ray (usually about a few tens keV) imaging, and showed such imaging detector suitable under many circumstances (Ikhlef et al., 2000; Ikhlef and Skowronek, 1998; Nasseri et al., 2004, 2005). However, the absorption efficiency of the fibers for higher energy γ-rays is greatly reduced because the fibers are made of mainly low mass elements. Thus, it is not clear if such an approach is suitable for hard γ-ray imaging. In this paper, we mainly focus on the detection efficiency (DE) of PSF for 100–10,000 keV mono-energy electromagnetic radiations, which is an extension of the previous study (Nasseri et al., 2005).

Scintillating fibers can be made of various materials, such as polymers and glasses doped with cerium or terbium

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0969-806X/$ - see front matter
doi:10.1016/j.radphyschem.2007.09.005

to improve their photoelectric absorption (White, 1988). In our simulation, we choose one of the most common and commercially available PSFs, BCF-20. The core of the fiber is made of polystyrene doped with 1% butyl-phenyl-byphenylyloxadiazole (PBD). The refractive index and the density of the fiber are 1.60 and 1.05 g/cm^3, respectively. Pure PS has an emission spectrum in the range of 300–350 nm, being inadapted to the most common photodetectors. So, it is usually necessary to dope PS with about 1% by weight of some primary fluor to reach a scintillation efficiency of about half of that crystalline anthracene and with about 0.01% by weight of secondary fluor which shift the light emitted by the first fluor to the region of maximum sensitivity of the absorption region of the photodetector (White, 1988). The cladding material of BCF-20 fiber is polymethylmethacrylate (PMMA) and has refractive index of 1.49. The thickness of the cladding layer is about 3% of core diameter. The calculated numerical aperture of the fiber is 0.58, the number of emission light is about 8000 per MeV photon, the emission spectrum is peaked at 492 nm, and the decay time is 2.7 ns, according to the manufacturer.

2. Simulation

The Monte Carlo simulation was carried out using Geant4 (Geometry And Tracking 4) which is a simulation toolkit package based on object-oriented technology (Geant4 Collaboration, 2003). The software was designed initially for simulating and studying the performance of detectors for nuclear and high energy physics experiments (Geant4 Collaboration, 2003, 2006). The program nowadays finds a wide range of applications such as radiation analysis, space and cosmic ray analysis and, more recently, medical oncology analysis and evaluations (Carrier et al., 2004; Tang et al., 2006). The program was developed at the European Organization for Nuclear Research (CERN) and is freely available on the Internet. The program has been carefully tested, the results obtained using this program are found to be consistent with those obtained using other programs (Carrier et al., 2004).

The design and the accessibility of the software provide transparency for implementation of various physics parameters and allow an easy understanding of physics model used (Geant4 Collaboration, 2003). A set of models that describe the interaction of photons and electrons with matters at various energies have been implemented in the toolkit. When an γ-ray enters a material, the photon interacts with the material through several physical processes, such as photoelectric effect, Compton scattering, Rayleigh scattering, Bremsstrahlung and ionization (Knoll, 1989), and all these physical processes are involved in Geant4.

A low energy limit for particle interaction corresponding to the minimal energy within the validity range of the model is defined. In our simulation, we set the range cut to be 0.1 mm for all the particles. Such a range corresponds to a low energy limit of 1 keV for photons in PSF. We found that as long as the fiber diameter is much larger than the range cut, the simulated energy deposition is not sensitive to the range cut chosen. The minimum diameter of the fibers simulated in this work is 1 mm. Thus, the results obtained using the 0.1 mm range cut should be reliable.

The experimental setup defined in Geant4 simulation is shown in Fig. 1, and the internal refraction of the optical photons in PSF is also described. The radiation source is treated as a point-like source. The length and diameter of the fiber are chosen to be 10 cm and 1 mm, respectively. The simulated results are not strongly affected by the length of the fibers, since in the energy range chosen here the energy deposition increases slowly with the length of a PSF (Ikhlef and Skowronek, 1994).

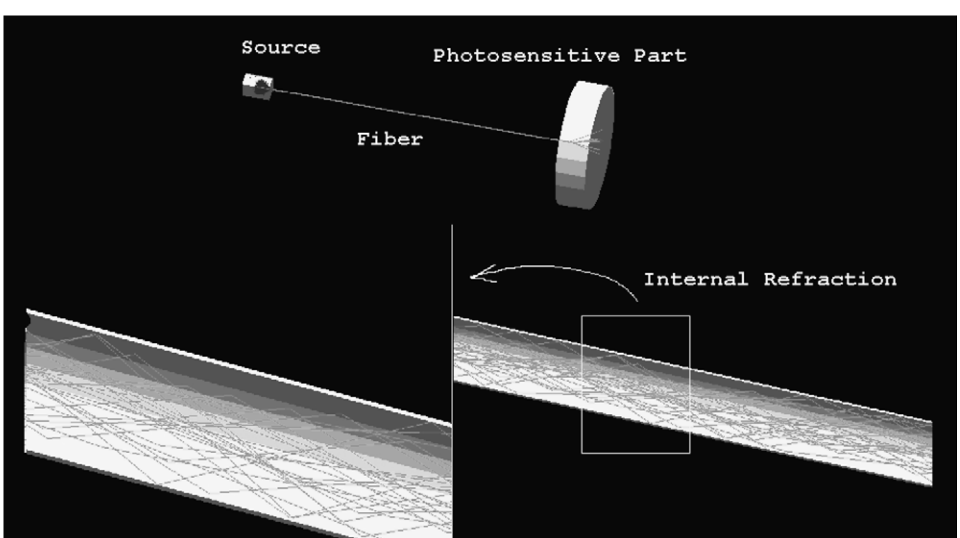

Fig. 1. The experimental setup in Geant4 simulation, and the internal refraction of the optical photons in PSF.

3. Results and discussion

In order to characterize the DE of the PSF, we first used the simulation to investigate the intrinsic efficiency versus incident photon energy. The intrinsic efficiency represents the probability of an incident photon generate a good event in the fiber. In the other word, it represents the ratio of number of interacted photon versus number of total incoming photons. Fig. 2 plots this ratio of a PSF with 1 mm diameter and 10 cm length. The figure demonstrates that intrinsic detecting efficiency of a PSF decreases rapidly with incident photon energy larger than a few hundreds keV. For incident photons with 10 MeV energies, the efficiency drops to only about 20%. The low efficiency is mainly due to the fact that PSFs are made of light elements which are not efficient in stopping high energy photons. For 1 MeV photons, nearly 50% are not detected as they pass through a 10 cm long and 1 mm diameter PSF, as shown in Fig. 2.

DE, or the overall scintillating detective efficiency, is defined as DE = scintillation output energy/photon input energy (Green, 2000), or

$$\mathrm{DE} = T_a \times T_c \times T_t, \tag{1}$$

where T_a is the absorption efficiency, defined as the ratio of the absorbed photon energy and the incident photon energy; T_c is the light conversion efficiency, defined as the ratio of generated scintillation light energy and the absorbed photon energy; and T_t is the transmission efficiency, defined as the ratio of the output scintillation light energy and the generated scintillation light energy (Knoll, 1989).

First, we obtained the absorption efficiency for different incident photon energy in a PSF from the output of Geant4 program, showed in Fig. 3. The figure shows that T_a drops with energy increases, and reaches a minimum at about 70 keV, and then slowly increases and finally drops again as the energy is above about 500 keV. This is caused by the dominating interactions of photons with PSF at different energies. For a photon below several tens keV, the photoelectric effect dominates in PSF, a low-Z material (Knoll, 1989; Green, 2000). As the photon energy increases, Compton effect becomes the dominated interaction and the T_a slowly increases to form a small bump at about 700 keV. Simulated separation of the photoelectric and Compton effects is plotted in Fig. 4.

Fig. 5 shows the absorption coefficient of polystyrene, which is the dominating component of PSF, versus photon energy (Scheirs and Priddy, 2003). As can be seen, there exists a maximum at about a few hundreds keV of the absorption coefficient of polystyrene, which is consistent with the simulated results.

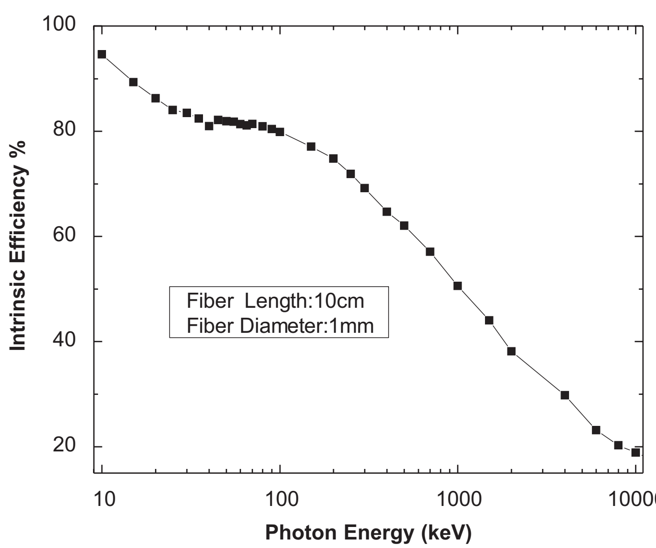

Fig. 2. Simulated intrinsic total efficiency of PSF versus incident photon energy.

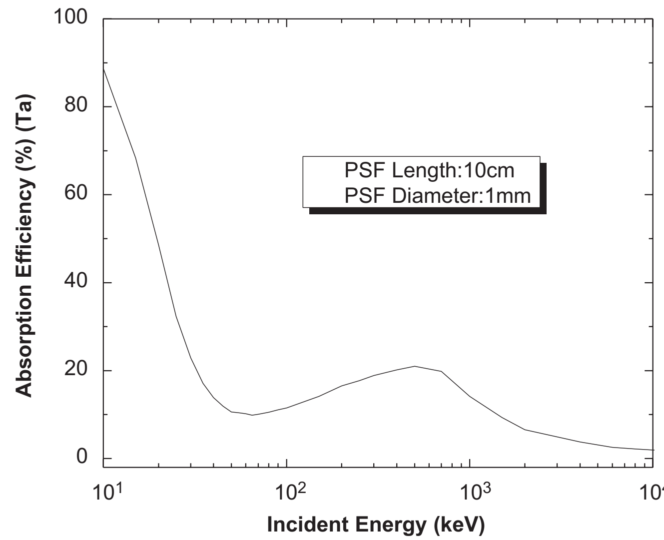

Fig. 3. Simulated absorption efficiency (T_a) of PSF versus incident photon energy.

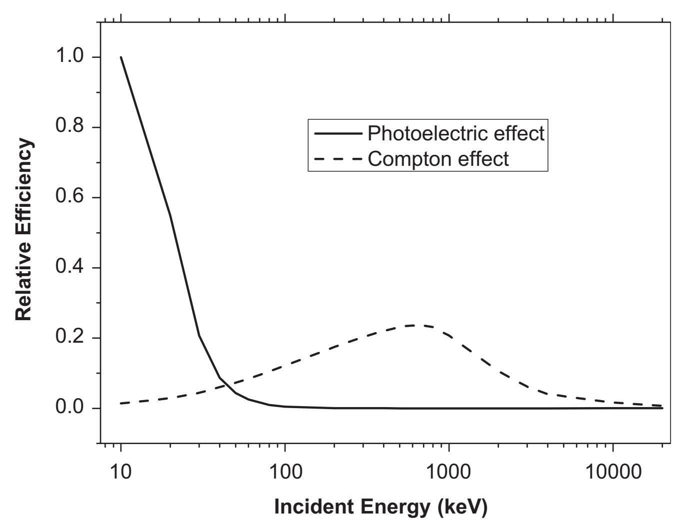

Fig. 4. Simulated separation of photoelectric and Compton effects contributing to relative efficiency versus incident photon energy.

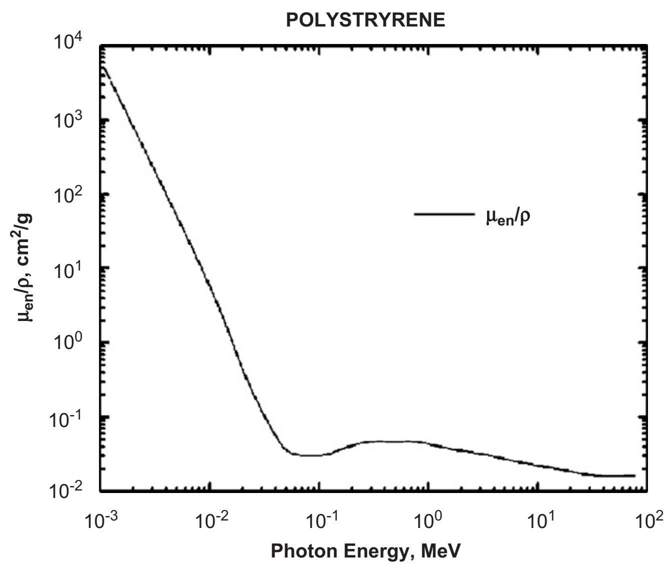

Fig. 5. Absorption coefficient of polystyrene versus photon energy.

For organic scintillators, the relation between the emitted light and the energy deposited by an ionizing particle is not linear. The scintillator response depends also on the type of particle and its specific ionization (Leroy and Rancoita, 2004). The response can be described by a relation between $\mathrm{d}L/\mathrm{d}x$, the fluorescent energy emitted per unit path length, and $\mathrm{d}E/\mathrm{d}x$, the specific energy loss for the charged particle. A widely used relationship first suggested by Birks is based on the assumption that a high ionization density along the track of the particle leads to quenching from damaged molecules and a consequent lowering of the scintillation efficiency,

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S(\mathrm{d}E/\mathrm{d}x)}{1 + kB(\mathrm{d}E/\mathrm{d}x)},$$

which is commonly referred to as ‘‘Birks’ formula’’. If we assume that the density of damaged molecules along the wake of the particle is directly proportional to the ionization density, the light yield is proportional to energy loss:

$$\frac{\mathrm{d}L}{\mathrm{d}x} = S\frac{\mathrm{d}E}{\mathrm{d}x},$$

where S is the normal scintillation efficiency (Leroy and Rancoita, 2004).

For BCF-20, the energy of the visible photon is 2.5 eV. By multiplying this value and the total number of photons produced in the fiber, one can find the fraction of the kinetic energy converted into light energy. The scintillation efficiency or amount of light generated per unit energy loss ($\mathrm{d}L/\mathrm{d}E$) depends on both particle type and its kinetic energy.

The light photons in fiber emitted by the interaction are distributed isotropically. All the photons in solid angle θ (critical angle) could be trapped by the fiber. With the values of the refraction indexes of the fiber core and cladding, one can easily derive the trapping efficiency of the fiber from formula:

$$T_{\mathrm{trap}} = \frac{1 - (n_{\mathrm{clad}}/n_{\mathrm{core}})}{2}. \quad (2)$$

The refraction indexes of our fiber (BCF-20) are $n_{\mathrm{core}} = 1.6$ and $n_{\mathrm{clad}} = 1.49$. So the trapping efficiency of the fiber would be 3.4%. In addition, the light energy transmitted along the fiber to the photo-detector is attenuated by absorption in the fiber core and light scattering. We expect this absorption value approx 1 because the fiber is only 10 cm long in this study.

Then the output light efficiency should be $T_{\mathrm{c}} \times T_{\mathrm{t}} = (\mathrm{d}L/\mathrm{d}E) \times T_{\mathrm{trap}}$. Fig. 6 shows the simulated output optical photon number versus depositing energy. By linear fitting of the curve in Fig. 6, we get the average value of the $T_{\mathrm{c}} \times T_{\mathrm{t}}$ being about 0.25 (light photon per keV). As can be seen, there is a good linearity when the energy deposition is higher than a few hundreds keV.

We should notice that there exists a discrepancy between the $T_{\mathrm{c}} \times T_{\mathrm{t}} = 0.9$ obtained for lower energy range (Nasseri et al., 2005) with that of 0.25 in this study. The main reason should be the different dominating effects and kinetic energy of ionizing electron. For 100–10,000 keV photons in this study, the dominant effect is the Compton scattering and the kinetic energy of secondary electron should be much higher than that previous report which considered 10–100 keV photons, with dominating photoelectric effect.

On the other hand, the ionizing electrons from Compton scattering in this study should be more accordant with the minimum ionizing particle (MIP), which typically refers to a few MeV per unit cm material. According to the manufacturer, the number of emission light is 8 photon per keV of deposited energy for MIP, so the theoretic value of $T_{\mathrm{c}} \times T_{\mathrm{t}}$ should be about:

$$T_{\mathrm{c}} \times T_{\mathrm{t}} = 8 \times 3.4\% = 0.272 \text{ (light photon per keV)},$$

which is consistent with the simulation value.

Now we are able to get DE of the PSF. DE versus incident photon energy, obtained using the results of

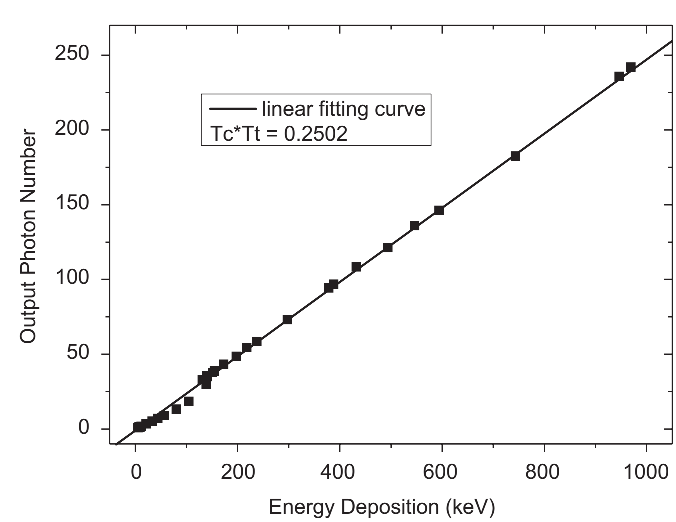

Fig. 6. Scintillating response versus depositing energy for PSF.

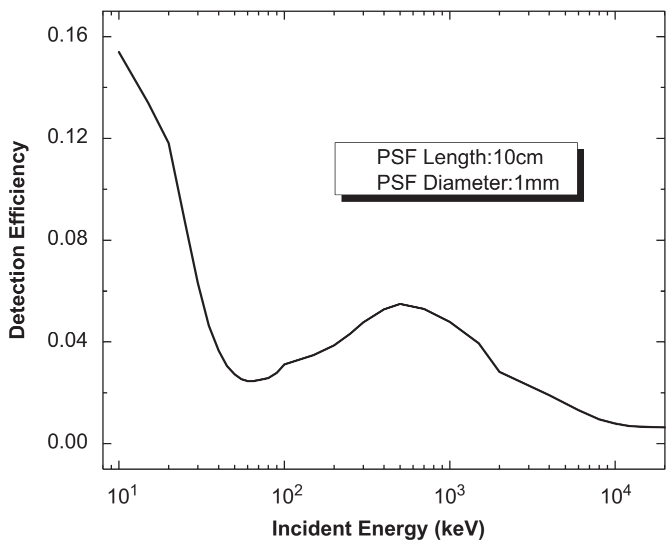

Fig. 7. Simulated detection efficiency of PSF versus incident photon energy.

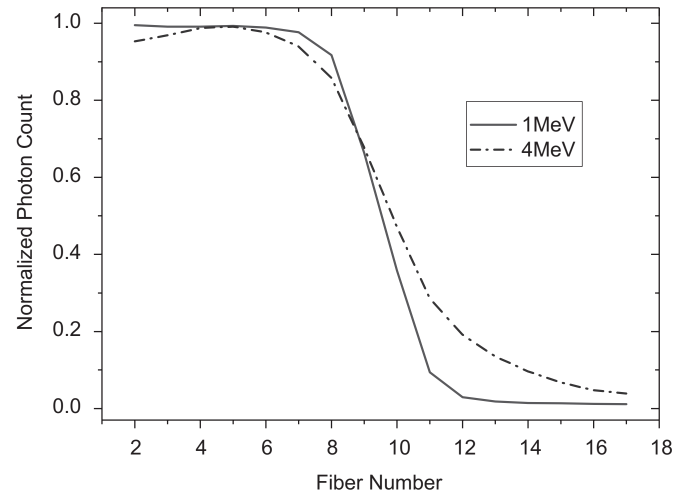

Fig. 8. Normalized profiles of photon output for 1 and 4 MeV.

simulation, is shown in Fig. 7. The main line shape of the DE is very similar to that of T_a, so the main important factor of the DE is the absorption efficiency of the scintillating material. On the other hand, $T_c \times T_t$ is almost constant in the incident photon energy range of 100–10,000 keV.

Another potential problem is the photosensitive DE, which we did not consider in this research. However, each photosensitive detector such as photomultiplier or CCD has its own detective efficiency value, which can finally make the DE of whole imaging system further worse.

As described above, the absorption efficiency is quite low when the energy of incident γ-rays is higher than a few hundred keV. When a photon enters a fiber array, it interacts with atoms/molecules, producing secondary photons which are emitted in random directions. The secondary photons can enter the neighboring fibers, producing an effect called cross talk between adjacent channels (fibers). When the cross talk is severe, the deterioration of the resolution can limit its use for several applications. It is clear that the higher energy of incident photons, the more severe cross talk will occur.

To investigate the general behavior of the cross talk, we simulated one-dimension profile of the light photon output in a scintillating fiber array. We choose certain line as a boundary, and the photons are incident in only one side of the array. The normalized profiles for different energies (1 and 4 MeV) are presented in Fig. 8. As can be seen, when the incident energy is higher, the profile is more gradient, which is possibly caused by the more severe cross talk.

One method that may have the potential in reducing cross talk is to place thin septa between the scintillator, which has been proposed in previous reports (Li et al., 2003; Izumi et al., 1993). However, the coated layer will also reduce the effective detecting area of the fiber array detector translating into an increased pixel size, which will finally affect the spatial resolution. Previous reports (Izumi et al., 1993; Melnyk and Dibianca, 2003) have shown that the reduction of cross talk can be improved with the use of tungsten as the coating material since it has a much higher γ-ray stopping power. In addition, using multi-cladded fibers in which cross talk can be significantly reduced (White, 1988) may also improve the performance of a fiber array detector for high energy γ-ray imaging. These possibilities will be systematically investigated in future work.

4. Conclusion

In summary, the absorption efficiency and scintillating response of the PSF for γ-ray radiation are obtained through Geant4 simulation. The DE of PSF is low for incident γ-rays with energy higher than a few hundreds keV. The simulated results are consistent with the theoretic ones to some extent, and the main important factor of DE in the energy range is the absorption efficiency of the scintillating material. The cross talks between adjacent fibers are also discussed. The main advantage of the PSF is its simplicity and low cost, so scintillating fiber as an γ-ray imaging detector may be useful under certain circumstances.

Acknowledgments

This work is supported by National Natural Science Foundation of China (No. 60602065) and by Innovation Funds of USTC for Graduate Student (No. KD2006009).

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